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This article, produced by NACE International Task Group 304, discusses the general industrial practice currently recommended by experts in the field of microbiologically influenced corrosion (MIC). Part 1 covers the best available techniques and strategies for handling MIC problems. It summarizes prevention and monitoring and gives published references where detailed descriptions of useful techniques may be found. Part 2 will deal with failure analysis and control.

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PART 1

Expert Consensus on MIC: Prevention and Monitoring

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This article, produced by NACE International Task Group 304, discusses the general industrial practice currently recommended by experts in the field of microbiologically influenced corrosion (MIC). Part 1 covers the best available techniques and strategies for handling MIC problems. It summarizes prevention and monitoring and gives published references where detailed descriptions of useful techniques may be found. Part 2 will deal with failure analysis and control.

During the CORROSION/2003 meeting of the NACE technical committee on Microbiologically Influenced Corrosion (MIC), several people expressed the opinion that information on MIC has not been adequately disseminated within industry. Although experts in the field have tremendous knowledge of how to monitor, diagnose, and control MIC, there is a perception that industrial practice falls far short of appropriate action.

The problem is not a new one. A 1993 *MP* Viewpoint article[1] bemoans the discrepancy between the extensive knowledge of MIC experts and the actual practice of MIC monitoring and control in industry. In recent years, tremendous advances have been made to improve knowledge of the causes and mechanisms of biological corrosion and to develop better monitoring techniques, biocides, and other control measures. The article states:

"The problem with all these advances is that the message is being rehearsed in the inner circles of MIC conferences but is not being taken swiftly enough to the people who would benefit most at the design, engineering, and plant levels. Although many have jumped on the buzz-word bandwagon, there are too few instances of the difficult task of sampling and diagnosing of MIC being taken seriously.

"It is no surprise that some people would prefer to ignore the fact that biological corrosion is a complex and difficult field. A reluctance to delve into the unpredictable realm of biology is no excuse, however, for ignoring unexplained corrosion problems; and it is no reason to avoid adequate diagnosis, monitoring, and treatment of MIC. We, as practitioners of solutions to MIC problems, are using these new advances but have not succeeded in encouraging their widespread understanding and use."

The committee established Task Group 304, "State of the Art in MIC Corrosion Monitoring and Control," with the goal of writing a technical article on industrial practice currently recommended by experts in the field of MIC. This is the first installment of that two-part article. It gives the group's recommendations on the best practice in MIC prevention and monitoring, referring—where necessary—to already-published and available information.

Where MIC Problems are Likely to Occur

Although MIC can occur in unexpected places, it tends to occur repeatedly at certain locations. Table 1 lists potential problem areas by industry.

In general, MIC problem areas for many industries occur more often in the following situations:

- In welds and heat-affected zones
- Under deposits
- After hydrotesting, if equipment is not drained and dried
- When cooling systems are not passivated after turnarounds are complete.

How to Prevent MIC

The keys to MIC control are system design, maintenance/cleanliness, and water quality.[2]

Whenever possible, system design should include:

- Appropriate materials selection. Stainless steel, for example, is less susceptible to general corrosion but more susceptible to pitting than carbon steel. Titanium has been found to be resistant to both forms
- Accessibility for cleaning, including access ports for pigs and blasting or water jetting
- Accessibility for water treatment, including systems for filtration and settling of suspended solids, chemical additions, and monitoring equipment
- Provision for drains, traps, recycle circuits, and monitoring equipment
- Control of water velocity and elimination of stagnant, low-flow areas and dead legs
- Minimization of crevices and welds.

Good housekeeping often is the key to MIC prevention and control. The system should be as free of sludge, deposits, and foulants as possible. Regular cleaning, including chemical and mechanical cleaning, should be part of the operating routine. Vigilance is essential in keeping the system clean, so monitoring programs should be instigated and maintained.

Good housekeeping sometimes can mean keeping the system dry. MIC after hydrotesting is a common problem where the system was not completely dried after testing. During wet lay-ups and outages, when it is not possible to dry the system, it may be necessary to add a long-acting biocide immediately prior to shutdown.

Water quality should be maintained at a high level. Methods to enhance water quality may include:

- Selecting the cleanest possible water source
- Using settling tanks and filtration systems to remove particulates
- Removing contaminants and nutrients such as oils, iron, phosphate, and nitrate
- Applying chemical treatment to reduce hardness, remove oxygen, or alter pH
- Adding biocide and inhibitor.

Detecting MIC Problems

Early detection of MIC problems is an important component in cost-effective MIC management. Whether a system already has had MIC problems or whether MIC is a known problem in the industry that one should test for in a new installation, the recommended best practice follows.

In bulk liquids, it is necessary to monitor physical, chemical, and biological characteristics on an ongoing basis. To monitor surfaces, corrosion coupons should be installed for regular monitoring and, in addition, the actual surfaces should be checked when equipment is opened or exposed. Details of these procedures are given below.

MONITORING BACTERIA IN BULK WATERS/LIQUIDS

The aim of water monitoring is to identify factors in the bulk water/liquids that may promote bacterial growth and attack, to identify potential problem organisms, and to detect trends in their quantity/abundance as they enter the system. All water quality parameters that are considered important to understanding internal corrosion and MIC for a particular type of industrial system should be monitored routinely and frequently (approximately weekly). Temperature, pH, anions, cations/metals, alkalinity, total suspended and total dissolved solids (TDS), dissolved gases (carbon dioxide [CO_2], hydrogen sulfide [H_2S], O_2, etc.), total organic and dissolved organic carbon, turbidity, and microorganisms (bacteria, algae, and fungi) all may be useful in obtaining clues to the health of a particular system.

Dissolved oxygen often is not particularly representative of the microenvironments where corrosion may be occurring. Biofilms can sequester anaerobic bacteria in deoxygenated environments even in waters supersaturated with oxygen. Some workers also have found that chemical oxygen demand (COD) may be a useful indicator of water quality in cooling water systems. COD content may measure the concentration of electron donors available for sulfate or metal reduction. Hence a low COD means a low risk of finding sulfate-reducing bacteria (SRB), iron-reducing bacteria, etc.

Additional parameters may be measured in specific systems—for example, sulfide, nitrite, ammonia (NH_3), and product in chemical process and oil and gas industries. Changes in these numbers, especially long-term trends in one

TABLE 1

WHERE MIC PROBLEMS ARE MOST LIKELY TO OCCUR

Industry/Application	Potential Problem Sites for MIC	Organisms Responsible
Pipelines—oil, gas, water, wastewater	Internal corrosion primarily at the bottom (6:00) position Dead ends and stagnant areas Low points in long-distance pipes Waste pipes—internal corrosion at the liquid/air interface Buried pipelines—on the exterior of the pipe, especially in wet clay environments under disbonded coating.	Aerobic and anaerobic acid producers, SRB, manganese and iron-oxidizing bacteria, sulfur oxidizing bacteria
Chemical process industry	Heat exchangers, condensers, and storage tanks—especially at the bottom where there is sludge build-up Water distribution systems (See also "Cooling Water Systems," "Fire Protection Systems," and "Pipelines" in this table)	Aerobic and anaerobic acid producers, SRB, manganese, and iron-oxidizing bacteria In oil storage tanks also methanogens, oil-hydrolyzing bacteria
Cooling water systems	Cooling towers Heat exchangers—in tubes and welded areas—on shell where water is on shell side Storage tanks—especially at the bottom where there is sludge build-up	Algae, fungi, and other microorganisms in cooling towers Slime-forming bacteria, aerobic and anaerobic bacteria, metal-oxidizing bacteria, and other microorganisms and invertebrates
Fire protection systems	Dead ends and stagnant areas	Anaerobic bacteria, including SRB
Docks, piers, oil platforms, and other aquatic structures	Just below the low-tide line Splash zone	SRB below barnacles, mussels, and other areas sequestered from oxygen
Pulp and paper	Rotating cylinder machines Whitewater clarifiers	Slime-forming bacteria and fungi on paper-making machines Iron-oxidizing bacteria SRB in waste water
Power generation plants	Heat exchangers and condensers Firewater distribution systems Intakes	As above for heat exchangers and fire protection systems Under mussels and other fouling organisms on intakes
Desalination	Biofilm development on reverse osmosis membranes	Slime-forming bacteria

direction or large anomalies, should be cause for further investigation. Correlate water quality measurements with microbial counts. Bacteria may increase, for example, during influxes of particulates into the cooling water system in windy seasons. Bacterial numbers also tend to be strongly correlated with temperature.

Monitoring Equipment

Water-monitoring equipment is readily available from commercial sources, and standard practices are available. Online monitoring of these parameters is ideal, but the equipment is more expensive and may have limitations in gas or liquid hydrocarbon environments. Many operators reduce costs by measuring parameters such as temperature, pH, conductivity, and TDS with online monitors, using portable or laboratory spectrophotometers and kits for the rest.

Bacterial Counts

The most important thing to remember about bacterial counts is that the actual numbers often are virtually meaningless. Culture media provide optimum growth conditions for only a small percentage of known bacteria. Under the best conditions, media usually only count ~10% of the viable bacteria present—and 1% may be more typical. Some other, direct-count techniques determine numbers of bacteria but do not distinguish between live and dead cells. Direct counts also can be difficult or impossible in turbid waters, and most direct-counting techniques require a microscope and stains (which many plants do not have). Far more important is the trend of increasing or decreasing numbers, which only can be established by consistent and conscientious monitoring. When applied carefully and consistently, bacterial monitoring in waters can be a useful technique. For example, the almost universally applied limits for total viable count incubation on yeast extract media—<10 per mL at 37°C for 24 h—have been very successful in monitoring and controlling potable water contamination.

Planktonic bacterial counts, as a tool for predicting the occurrence of bacterial corrosion, have been much maligned in recent reviews of bacterial monitoring. At least some of the bad experiences with planktonic counts, however, result from poor techniques and practices. In counting bacteria, technician training and consistent sampling/culture methods are vital aspects

of program success. As a measure of changing system conditions, planktonic counts can provide useful data—but only if measured rigorously. Samples should be collected in the same way and from the same place, incubated for the same time and at the same temperature in the same medium, and counted by the same operator. Errors introduced by changing these variables can be so large that they may override or confuse any actual changes in the system, rendering the monitoring program useless. Correct procedures, carried out by trained technicians, are important; in the group's experience, however, this factor rarely is recognized by technicians or even management in the field.

Do not change the method of collection, culture, or measurement of the system unless necessary. There is a very poor correlation between bacterial numbers counted with various commonly used culture media, and the resulting differences are neither consistent nor predictable. If necessary, check the effect of the new conditions by overlapping the two methods until the relationship between the two results becomes clear.

One of the most common counting methods for aerobic systems is measuring the number of colony forming units (CFU) per milliliter of bulk water on standard culture plates or dip slides. CFUs generally count the number of heterotrophic, aerobic bacteria that are culturable on standard media plates (such as trypticase soy agar or in nutrient broth). Dip slides are more convenient because they eliminate the need to accurately measure a known quantity of water, but are more expensive. Aerobic bacteria test results usually are obtained in 1 to 3 days. Anaerobic bacteria typically are cultured in liquid media, in which it is easier to exclude oxygen—at least at the bottom of the culture tube. Anaerobic bacteria test results are obtained in a few days—longer in the case of SRB (up to 28 days). The most widely used technique for counting bacteria in liquid cultures is the most probable number (MPN) technique. However, MPN may be difficult to use in very turbid liquids.

Culture Techniques

Because microorganisms grow selectively on various media, it is necessary to culture a wide variety of potential corrosion-causing microbes—at least initially. Depending on the environment being tested, monitoring programs may include media for general aerobic bacteria, general anaerobic bacteria, acid-producing bacteria, sulfur-oxidizing bacteria, SRB, fungi, algae, and any other groups that have been suspected to be a problem in the system. If some of the media routinely produce negative results, they can be dropped from the regular monitoring program but still should be checked occasionally. General aerobic or anaerobic bacteria counts and SRB counts should be continued in most cases, however.

Because of the limitations of culture techniques, bacterial culturing is not the only recommended method for monitoring MIC. Nonassay techniques should be used, such as coupons, visual inspection, linear polarization probes, and any other available clues.[3]

Adenosine triphosphate photometry, respirometry, fluorescent dyes, specific antibody tests, and redox indicator tests are faster techniques, measuring biomass in ~10 min; however, they are more expensive, require sophisticated equipment and/or techniques, and have detection limits that are quite high. Recently, fluorescent bio-reporters also have been used to measure total biological activity online.

MONITORING DEVICES

Although sessile bacteria are recruited initially from bulk liquids, there usually is little correlation between the planktonic and sessile bacterial numbers. Therefore, sessile bacteria need to be monitored separately from bulk-water bacteria.

Sessile bacterial numbers should be sampled in the areas that are most susceptible to corrosion problems. Many monitoring programs include removable, in-process coupons or probes that typically are inserted into system piping/components or devices such as tubular flow systems, Robbins† devices, or Renaprobes† that are added to the system. The devices provide real-time data on the system conditions and can be used to gain information on biofilm development and corrosion rates. The probes also may be located in a side-stream device. Side-stream devices offer the additional advantage of allowing one to experimentally alter biocide levels and process conditions under controlled conditions, giving reasonably fast and reliable information on their effects on the system. Coupons have been found to be a useful and effective field-monitoring technique for MIC, as in other corrosion problems—especially when included in a larger monitoring program using several other supplementary techniques. Although it is not always possible to distinguish between MIC and other corrosion mechanisms, extended analysis of coupons using microscopic techniques can yield important evidence with regard to pit initiation mechanism(s). It also can identify the severity of localized attack through the measurement of pitting (pit densities, depths, and diameters), calculate pitting rates by bacteria or other corrosive components, and determine severity of attack.[4]

New Monitoring Techniques

One problem encountered with coupon and probe devices is that they are destructive and require time-consuming analysis. To obtain information on long-term buildup of biofilms, coupons must be removed sequentially, requiring placement of numerous coupons in the same location. The coupons then must be cultured for vari-

†Trade name.

ous bacterial groups. These shortcomings have led to many recent attempts to develop faster, more user-friendly methods of monitoring biofilm development.

Using DNA hybridization probes instead of culture methods shows considerable promise, although the probes only can detect total bacteria and/or specific genera of bacteria.[5] Probes have been developed to target 1) all eubacteria, 2) *Desulfovibrio desulfuricans* and SRB of the genus *Desulfotomaculum,* 3) SRB of the genus *Desulfobacter,* or 4) *Desulfovibrio desulfuricans* and SRB of the genus *Desulfobacter.* Because the use of multiple probes requires repeated analysis of a sample, reverse probe protocols have been explored. The protocols entail immobilizing a number of probes on a chip and hybridizing them to labeled components of the sample. For example, reverse sample genome probing, in which entire genome probes are immobilized, has allowed determination of multiple SRB species on a corrosion coupon in a single DNA hybridization assay.[6-7] The greatest breakthrough will come when samples can be assayed rapidly without prior growth. Bioinformatic analysis of sequenced microbial genomes and sequencing of all bacterial genomes in selected microbial communities, which may be expected in the near future, will spur development of increasingly useful chips. These chips would contain thousands of DNA probes that could be used to analyze the microbial community composition of corrosion coupons.

Some techniques have been developed for specific applications. An online monitoring system for corrosion and bacteria in oil and gas pipelines removes fluid from the pipe and separates the water for corrosion rate and bacterial analysis. Many techniques can be coupled to the system. They include coupons, electrical resistance probes, galvanic probes, hydrogen probes, linear polarization resistance, alternating current impedance spectroscopy, electrochemical noise, pH, and conductivity. Electrochemical probes detect the changes in applied current caused by biofilm activity on coupled stainless steel electrodes. In addition, generated current is a more sensitive indicator of biofilm activity.[8] These combined techniques have met with success in field applications.[9] Other, more complex electrochemical techniques, such as noise and impedance spectroscopy, generally are considered to be more suitable for research than field monitoring.

Another new online technique uses fluorogenic dye bioreporters, which react with planktonic and sessile microorganisms. Separate signatures identify the products before and after interaction with microbes and are expressed as a ratio.[10]

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